The Relevance of Biological and Hydrodynamic Timescale in the Growth of Plankton

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Abstract

The relationship between hydrodynamic mesoscale structures and plankton formation in the wake of an island, as well as its interaction with a coastal upwelling, is investigated. Our focus is on the process by which vortices create localized plankton blooms. A basic three-component model for marine ecology was utilized, as well as a coupled system of kinematic flow that mimicked the mesoscale features underlying the island. We show that the prevalence of localized plankton blooms is produced mostly by the prolonged residence times of nutrients and plankton in the island's vicinity, as well as the confinement of plankton within vortices.

Keywords

Plankton, Upwelling, Vortices, Nutrient, Limit Cycle

1. Introduction

The interaction between hydrodynamic velocity with the dispersion of marine creatures such as phytoplankton and zooplankton is a key topic that has lately been addressed in a number of studies ([1] [2] [3]).

The growth of phytoplankton in the world's seas is heavily reliant on nutrition availability. Thus, one of the critical variables influencing primary production is nutrient vertical transit. One of the most significant processes of this type is coastal upwelling. It mainly happens when wind-driven currents combine with the Coriolis force to generate Ekman transport, which drives surface waters away from the shore and replaces them with nutrient-rich deep waters. Because of this nutrient enrichment, primary production in these locations is greatly increased, resulting in an increase in zooplankton and fish populations.

On the other hand, some recent researches have looked at the interaction be-

tween plankton dynamics and horizontal transport, mixing, and stirring ([4] [5]). Horizontal agitation caused by mesoscale structures like as vortices and jets redistributes plankton and nutrients may boost primary production ([6]). Horizontal movement can also trigger phytoplankton blooms and influence competition and coexistence among plankton species ([7]).

Vertical upwelling in conjunction with intense mesoscale activity happens in a number of locations across the world. One of these areas is the Atlantic Ocean around the northwestern African coast, near the Canary Islands. The major water circulation in this area flows from the northeast towards the Canary Islands, leaving a wake of intense mesoscale hydrodynamic activity ([8]). The interplay between the vortices formed by the Canary Islands and the Ekman flow appears to be critical for the reported increase in biological output in the open southern Atlantic ocean around the Canary Islands ([9] [10]).

The purpose of this work is to investigate the relationship between plankton redistribution by vortices and primary production. We are particularly interested in the function of plankton particle residence periods in the wake of the island. Though we feel that our research is applicable to other parts of the world, we concentrate on the situation in the Canary Islands.

In this paper, we investigate the impact of the underlying hydrodynamic activity and nutrient upwelling on primary production in different areas of the wake by coupling the kinematic flow introduced in ([11]) to a simplified model of plankton dynamics with three trophic levels. Vortices have been found to have an important role in the improvement of primary production in this configuration. The principal objective here is to thoroughly examine this process and demonstrate that the longer residency durations of plankton within vortices are responsible for the detection of isolated algal blooms within them.

Hence, the key research questions or hypotheses being addressed in the study are as follows: How are limited plankton blooms affected by hydrodynamic flow and the presence of vortices in an island's wake? What is the time that plankton spends living in vortices and around the island? In terms of time scales, how do hydrodynamics and plankton growth interact?

These research questions aim to investigate the role of hydrodynamics and vortices in the formation of plankton blooms, the dynamics of plankton residency, and the impact on primary production. The study also explores the significance of the chaotic saddle and the interplay between hydrodynamics and plankton growth.

What follows is how the paper is organized. Section 2 describes the overall structure of our system, including the hydrodynamical and biological models, as well as their interactions. Our primary focus is on the mechanics of the formation of a limited plankton bloom within a vortex (Section 3). We investigate the residency durations of plankton within vortices and in the vicinity of the island. In addition, we elucidate the significance of the chaotic saddle imbedded in the flow in the island's wake. Finally, we summarize and discuss our findings.

2. Materials & Methods

Our system is made up of a hydrodynamic flow with a built-in obstruction and vortices in its wake. The model also includes a current perpendicular to the main flow that simulates an Ekman flow from the shore, as well as a nutrient-rich region away from the obstruction that simulates a coastal upwelling zone. Figure 1 shows a drawing of the model. We imitate the main aspects of hydrodynamic flow in the Canaries using this reduced geometry (notice that the entire Canary archipelago is mimicked by one cylindrical island). In particular, substantial mesoscale activity is observed in the wake of the obstruction in the form of a periodic detachment of vortices, which then move in the main flow direction.

We employ kinematic model, which we updated by including the Ekman flow ([11]). This model is linked to a basic population dynamics model that incorporates the interactions of nutrients N, phytoplankton P, and zooplankton Z. The following two subsections introduce both the hydrodynamic and biological models before addressing the findings of coupling both models to explore the feedback between hydrodynamics and phytoplankton development.

2.1. The Hydrodynamic Model

The velocity field is now introduced. Details are available in ([11]). Our hydrodynamic model is configured with a horizontal flow pattern. The major stream flows from left to right along the horizontal x direction, as seen in Figure 1. The origin of the coordinate system is located in the middle of the cylinder. We look at a two-dimensional velocity field that can be calculated analytically using a stream function. The velocity components in the x and y directions, as well as the equations of motion of fluid elements, are as follows:

$$\begin{cases} \dot{x}(t) = v_x(t,x,y) = \dfrac{\partial}{\partial y}\Psi(t,x,y), \\ \dot{y}(t) = v_y(t,x,y) = -\dfrac{\partial}{\partial x}\Psi(t,x,y) \end{cases} \tag{1}$$

The product of two terms yields the stream function ([12]):

$$\Psi(t,x,y) = f(x,y)g(t,x,y). \tag{2}$$
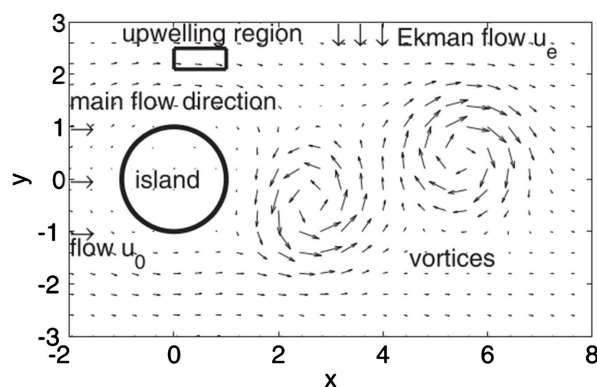
Figure 1. The simplified island wake model configuration.

The first component, $f(x, y)$, guarantees that the boundary conditions at the cylinder are accurate, $f(x, y) = 1 - \exp\left[-a\left(\sqrt{x^2 + y^2} - 1\right)^2\right]$. The second element, $g(t, x, y)$, represents the background flow, vortices in the wake, and the Ekman flow.

$g(x, y) = -\omega h_1(t) g_1(t, x, y) + \omega h_2(t) g_2(t, x, y) + u_0 s(x, y) y + u_E \Theta(x - 1)x$. The vortices in the wake have opposing signs, but their peak vortex strengths are equal and represented by ω, and its shape is given by the functions g_i. The standard linear dimension of the vortices is provided by $k_0^{-\frac{1}{2}}$, and the characteristic ratio of vortices elongation in the x and y directions is given by α. The vortex centers move in the x direction according to $x_1(t) = 1 + L(t/T_c \bmod 1)$ and $x_2(t) = x_1(t - T_c/2)$, and at values of $y_i(t)$ described below. Each vortex travels along the x direction for a time T_c and disappears. With a speed of u_0, the background flow travels in a positive horizontal direction. The phenomenological shielding of the background flow by the cylinder is described by the factor $s(x, y)$, which uses the same elongation factor α as the vortices. The Ekman drift is included to describe the flow from the shore to the ocean interior by incorporating an extra velocity of constant intensity u_E in the y direction operating solely at x coordinates greater than one, i.e. immediately behind the island. This refers to a stream crossing the vortex street and heading towards the cylinder's negative y values.

Real-world ocean currents are never completely periodic. As a result, we employ a non-periodic variation of the previously given kinematic flow. Non-periodicity is accomplished by randomizing the vortex paths. Rather than travelling in straight horizontal lines, $y_1(t) = y_0$, $y_2(t) = -y_0$ (y_0 constant), the vertical coordinates of the vortices move according to $y_1(t) = y_0 + \varepsilon\xi(t)$ and $y_2(t) = -y_1(t)$ where, at each time, $\xi(t)$ is a uniform random number in the range $[-1, 1]$, and ε is the noise strength.

The model's parameters are designed in such a way that they accurately depict the geophysical aspects of the Canary zone. Table 1 shows these values. We measure all lengths in units of the island radius $r = 25 \text{ km}$ and all periods in units of the period $T_c = 30$ days to make the model dimensionless. We refer to ([11]) for a detailed explanation of all parameters and the model's adaption to the scenario around the Canary Islands.

2.2. The NPZ Biological Model

A wide range of models for analyzing the dynamics of marine ecosystems may be found in the literature. Their complexity ranges from simple with only a few interacting components ([13] [14]) to huge with many interacting components ([15]). We utilize a system based on Steele and Henderson's (1992) three-component model, which was later refined by (Edwards and Brindley, 1996) and (Oschlies and Garcon, 1999).

The model illustrates the interaction of three species in a trophic chain,

Table 1. Parameters utilized in the hydrodynamical model.

Parameter	Value	dimensionless Value
r	25 Km	1
u_0	0.18 m/s	18.6
$k_0^{-\frac{1}{2}}$	25 Km	1
α	1	1
ω	55×10^3 m²/s	200
T_c	30 days	1
L	$6r = 150$ Km	6
$a^{-\frac{1}{2}}$	25 Km	1
u_E	0.02 m/s	2
y_0	$r/2 = 12.5$ Km	0.5
ε	6.25 Km	0.5

namely nutrients N, phytoplankton P, and zooplankton Z, whose concentrations change over time according to the dynamics described below:

$$
\begin{cases}
\dfrac{dN}{dt} = F_N = \Phi_N - \beta \dfrac{N}{k_N + N} P + \mu_N \left((1-\gamma) \dfrac{\alpha \eta P^2}{\alpha + \eta P^2} Z + \mu_p P + \mu_Z Z^2 \right), \\[3mm]
\dfrac{dP}{dt} = F_P = \beta \dfrac{N}{k_N + N} P - \dfrac{\alpha \eta P^2}{\alpha + \eta P^2} Z - \mu_P P, \\[3mm]
\dfrac{dZ}{dt} = F_Z = \gamma \dfrac{\alpha \eta P^2}{\alpha + \eta P^2} - \mu_Z Z^2
\end{cases}
\tag{3}
$$

Let us now go over the definitions of the various terminologies (for more information, see [16] [17]): The dynamics of nutrients are determined by nutrient supply owing to vertical mixing, bacterial recycling, and phytoplankton eating. Because the hydrodynamical element of the model only examines horizontal transport of nutrients, vertical mixing that transfers nutrients from lower levels of the ocean into the mixed layer is parameterized in the biological model. We assume N_0 as a constant nutrient content below the mixed layer for vertical mixing. As a result, the mixing term is as follows:

$$
\Phi_N = S(x, y)(N_0 - N). \tag{4}
$$

where S is the function that defines the intensity of the upwelling and will be studied more later. Phytoplankton take nutrients with saturation characteristics indicated by a Holling type II functional response. The final three terms in the bracket represent bacterial recycling. Bacteria decompose a portion of all dead organic debris as well as zooplankton exudation, albeit the dynamics of the bacteria themselves are not included in the model. The phytoplankton grows by absorbing nutrients, but its concentration is reduced by zooplankton (grazing

term) and natural death. Grazing, represented by a Holling type III function, is also included as a growth term for zooplankton dynamics, multiplied by a factor γ that accounts for the fact that only a portion of the food is transformed into zooplankton biomass, while the remainder $(1-\gamma)$ is recycled. Natural zooplankton mortality is assumed to be quadratic since this term not only models natural mortality but also the presence of higher predators that are not explicitly included ([18]). **Table 2** shows the parameters that were utilized from ([17]). Although suitable for the open ocean, they would offer estimations for biological parameters in the Atlantic along the coast. Space is measured in units of r, time in units of T_o, and mass in units of $10^1 2$ mmol·N to generate dimensionless values that are handy for numerics.

In phytoplankton dynamics, primary production is defined as the growth term:

$$PP = \beta \frac{N}{K_N + N} P \tag{5}$$

Because it quantifies the local nutrient supply, the function S, which measures the intensity of vertical mixing in this model, is critical for the link between the hydrodynamical and biological models. As seen in **Figure 1**. We suppose that an upwelling zone exists in a tiny rectangular region on one side of the island. We assign two alternative values to the parameter $S(x, y)$ based on this assumption. There is substantial vertical mixing in the upwelling zone, resulting in nutrient-rich waters in the mixed layer. There, we assume $S(x, y) = S_h = 0.648\,\text{day}^{-1}$, however upwelling is considerably lower in the surrounding seas, so we assign $S(x, y) = S_l = 0.00648\,\text{day}^{-1}$, which is a hundred times lower.

These equations describe the interactions and feedback mechanisms between

Table 2. List of parameters used in the NPZ model.

Parameter	Value	Dimensionless Value
β	0.66 day^{-1}	19.8
η	1 (mmol·Nm^{-3})$^{-2}$ day^{-1}	0.122
γ	0.75	0.75
a	2 day^{-1}	60
S_l	0.0064 day^{-1}	0.19
S_h	0.64 day^{-1}	19.44
K_N	0.5 mmol·Nm^{-3}	7.8
μ_N	0.2	0.2
μ_P	0.03 day^{-1}	0.9
μ_Z	0.2 (mmol·Nm^{-3})$^{-2}$·day^{-1}	0.38
N_0	8	125

nutrients, phytoplankton, and zooplankton in a marine ecosystem.

In addition to the NPZ model, the study also utilized a kinematic flow model to simulate the hydrodynamic flow in the study area. The flow model included a built-in obstruction (representing an island) and vortices in its wake. It also incorporated a current perpendicular to the main flow, simulating an Ekman flow from the shore, and a nutrient-rich region away from the obstruction, simulating a coastal upwelling zone. The reasons for choosing these models were as follows:

- NPZ Model: The NPZ model is a well-established and widely used model for studying marine ecosystems. It captures the essential dynamics of nutrient availability, phytoplankton growth, and zooplankton consumption, allowing for the analysis of primary production and trophic interactions.
- Kinematic Flow Model: The kinematic flow model was chosen to simulate the hydrodynamic flow in the study area, specifically the wake of the obstruction (island). This model was selected because it accurately represents the observed mesoscale activity and vortex formation in the region, which is known to influence primary production.

By coupling the NPZ model with the kinematic flow model, the study aimed to investigate the relationship between plankton redistribution by vortices and primary production. The longer residency durations of plankton within vortices were hypothesized to be responsible for the detection of isolated algal blooms within them. The models were applied to explore this process and understand the mechanisms behind plankton bloom formation in the wake of an island.

The dynamics of this model vary based on the parameters used. Long-term behavior can be either stationary (constant N, P, and Z concentrations) or oscillatory. For further information, see [18] [19]. We apply a parameter configuration in which the system has a stable steady-state. Using the parameter values from Table 2 and the vertical mixing $S = S_l = 0.00648 \, \text{day}^{-1}$, we get $N_{amb} = 0.185$, $P_{amb} = 0.355$, and $Z = Z_{amb} = 0.444 \, \text{mmol} \cdot \text{N} \cdot \text{m}^{-3}$ as steady states. The ambient primary production in this nutrient-poor location is $PP_{amb} = 0.0633 \, \text{mmol} \cdot \text{N} \cdot \text{m}^{-3} \cdot \text{day}^{-1}$.

3. Results & Discussions

We now explore the behavior of the coupled biological and hydrodynamical system from several viewpoints to elucidate the mechanism of localized augmentation of phytoplankton and primary production associated to vortices. An algal bloom has no universally accepted definition. A bloom is often defined as a significant rise in phytoplankton concentrations. Due to seasonal forcing, such flowers are usually only seen once or twice a year. In our scenario, the phytoplankton bloom is not caused by an external force and occurs on a rather short time frame. We analyze the scenario when there is a significant increase in phytoplankton as a result of nutrient enrichment ([20] [21]).

The appearance of a strong increase in phytoplankton is a temporary pheno-

mena, and its time scale is important for the process of localized enhancement of the primary production because the long-term behavior of our model is stationary for the parametrization utilized. The upper portion of **Figure 2** depicts the temporal evolution of the three components and primary production PP of the model system towards the steady state concentrations C_{amb} ($C = N, P, Z$ or PP). With beginning concentrations of 0.01 steady-state concentrations of N_{amb}, P_{amb}, and Z_{amb}, the nutrient concentration increases first, followed by a time lag by a significant increase in primary production and phytoplankton concentration. When the nutrients are at their highest, the growth is roughly exponential. The bloom finally stops due to nutrient depletion and increased grazing by zooplankton with a longer time lag, as well as an increase in the concentration of predators (zooplankton). The time evolution of the system with beginning concentrations of 0.3 steady-state concentrations of N_{amb}, P_{amb}, and Z_{amb} is plotted in the lower panel of **Figure 2** for comparison. Because there are more predators already present, the overshooting in nutrient and phytoplankton concentrations at the beginning of the time evolution is less pronounced and the concentrations converge faster towards the steady-state with greater starting concentrations.

We can calculate the time scale for biological growth from these simulations: Depending on the beginning state, about 15 to 25 days are needed to reach the bloom's maximum. The duration of the entire relaxing process is around $2T_c$, or 60 days. We must contrast this biological time scale with the hydrodynamic one in order to comprehend how biological growth and hydrodynamic mesoscale structures interact.
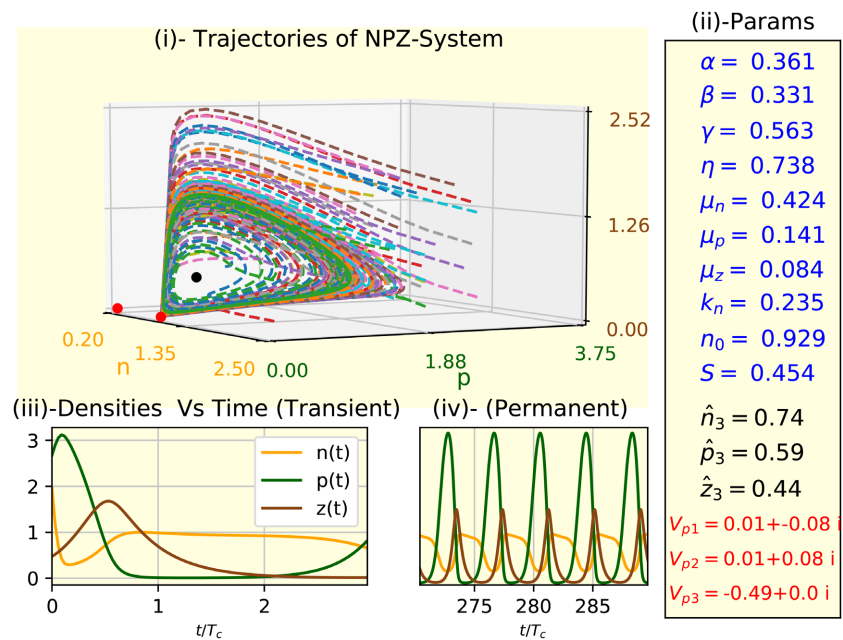
Figure 2. The time evolution of the concentrations (C) of the species and the primary productivity. Starting concentrations are 0.01× steady state concentrations of *N*, *P* and *Z* and 0.3× steady state concentrations of *N*, *P* and *Z*.

The improvement of primary production in the wake of the island depends on the hydrodynamic mesoscale structures, as mentioned in [11]. We now estimate the time scales for the pertinent hydrodynamic processes to get deeper understanding of how hydrodynamics and plankton growth interact. In order to achieve this, we investigate the numerous hydrodynamic flow configurations that significantly affect the length of time that nutrients and plankton spend in the wake of the island. First off, the flow is strain-dominated far from the island (top and bottom of Figure 1), and particles like nutrients and plankton are transported with the background flow of speed u_0. With $y > 2$ and $y < -2$, $x = 0$, the residence duration of particles dispersed away from the island is therefore around 16 days.

The presence of eddies is the second thing we observe. They stand out for having vorticity predominate over strain. As a result, once entrained to the vortex, particles are imprisoned within it. The particles will rotate in the vortex for a while, but since this confinement is imperfect and vortices only last for a short while, they eventually leave the vortex and exit the computational area with the background flow.

Thirdly, we take into account the chaotic saddle and the cylinder border, two additional geometrical elements that are also important for the residency period of particles in the vortex street. It has been demonstrated in ([12] [22]) that the flow beyond the island contains a chaotic saddle. This invariant set controls the residency durations of particles, at least for short time scales. The chaotic saddle will be approached along its stable manifold and left along its unstable manifold by particles that are released nearby. Because of the parameters employed here, the manifolds are closely clustered next to the cylinder as opposed to the setup in [12].

Finally, we go through how vital it is for nutrients to be mixed vertically in the upwelling zone in order for a plankton bloom to form inside of vortices. When comparing the left and right columns of Figure 3, it is clear that in the event of
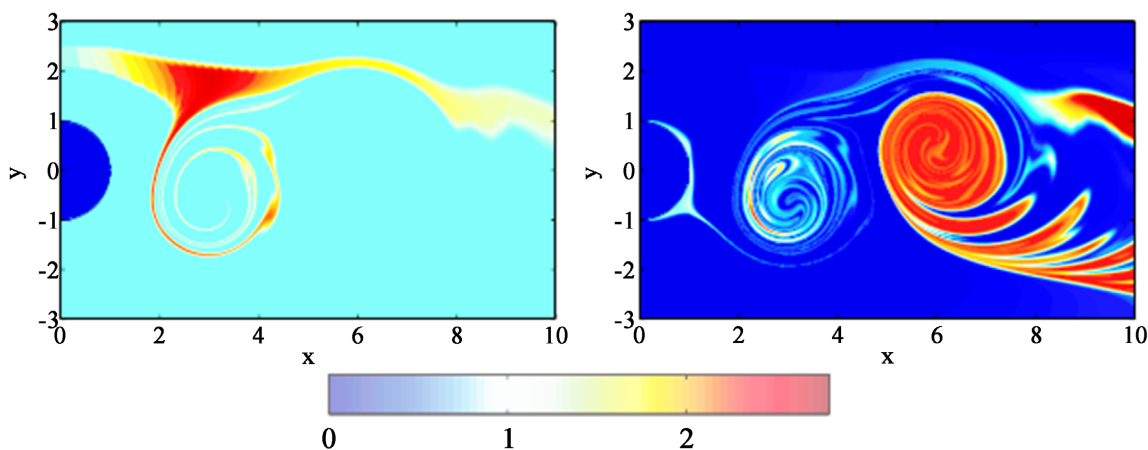
Figure 3. The phytoplankton concentration for inflow at ambient concentrations (left) and for low inflow concentrations (right), normalized with the steady state concentration, P_{amb}. Images captured at c $t/T_c = 4.1, 4.35, 4.6$, and 4.85.

an inflow under steady-state conditions (left column), a phytoplankton bloom (red filamental plume) is caused by the nutrient plume that forms in the area of the upwelling zone. Under low inflow circumstances, such a plume is essentially nonexistent (right column). Although the vertical mixing-induced nutrient supply is the same for both inflow situations, its impact seems to be lessened in the low inflow scenario. One defense has already been presented above: The very low plankton concentrations cannot increase to achieve high values during the time that it takes to pass through the computing area because the background flow delivers the nutrients too quickly.

This suggests that in the low input circumstance, the extra nutrients entrained from the upwelling zone have a minimal impact on the plankton bloom inside the vortex. However, there is no discernible change in the quality of the phytoplankton and zooplankton concentration values when compared to the upwelling regime. Thus, this mechanism can cause localized phytoplankton blooms in vortices in the wake of an island without any additional nutrient supply from upwelling.

Overall, these findings contribute to our understanding of plankton dynamics by elucidating the role of hydrodynamic activity, nutrient residence periods, and confinement within vortices in the formation of localized plankton blooms. They emphasize the complex interplay between physical processes and biological responses in marine ecosystems, shedding light on the mechanisms that drive plankton distribution and primary production.

4. Conclusions

Parameter values for the kinematic hydrodynamic flow were chosen to match the observations for the Canary island region. Our research focuses on the limited emergence of a plankton bloom in a vortex following an island. Here, we have described how such a plankton bloom works.

If a jet dominates the hydrodynamic flow distant from the island, the hydrodynamic time scale will be considerably faster than the biological one, making it impossible to see significant plankton growth. In contrast, a slower time scale that is comparable to biological time is obtained in the wake of an island, leading to an exponential development of phytoplankton and the emergence of a plankton bloom within a vortex. The primary causes of this phenomenon are the prolonged residence times in the area surrounding the island, which results in an enrichment of nutrients and plankton there; and the confinement of plankton in the vortex. Although localized plankton blooms are more likely to arise when nutrients are upwelled in an upwelling zone, this phenomena is not required for it to happen. It has been demonstrated that a plankton bloom can start inside a vortex when upwelling solely takes place precisely within the vortices.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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